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RESEARCH MEMORANDUM

EXPERIMENTAL EVALUATION BY THERMODYNAMIC METHODS OF WORK INPUT TO A CENTRIFUGAL COMPRESSOR OPERATING WITH WATER INJECTION

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EXPERIMENTAL EVALUATION BY THERMODYNAMIC METHODS OF WORK INPUT TO A CENTRIFUGAL COMPRESSOR OPERATING WITH WATER INJECTION

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SUMMARY

A thermodynamic method of determining the work input to a centrifugal compressor operating with water injection is presented. The method was used to compute the work input to a double-entry centrifugal compressor, which was operated at design equivalent impeller speed over a range of inlet water-air ratios and varying weight flow. The work input as determined in this manner agreed quite well with a measured shaft input when the concentration of water droplets at the compressor-outlet measuring station was small. As the concentration was increased, a more pronounced scattering of the data resulted.

INTRODUCTION

Injection of water at the compressor inlet introduces difficulties in the determination of the state of the water-air mixture at the compressor outlet and in the computation of enthalpy change. Because the percentage of water evaporated has been an indeterminate factor, the evaluation of enthalpy increase for each of the constituents of the mixture at the compressor outlet (namely, water droplets, water vapor, and air) cannot be determined from instrumentation conventionally employed. The assumption of complete evaporation and the use of temperature measurements from conventional unshielded thermocouples may introduce errors in the computation of work input of the order of 40 percent. Mechanical means of measuring torque can be employed to determine the compressor work input; however, it is not always feasible to install the necessary devices on a composite engine.

The results of an investigation conducted at the NACA Lewis laboratory in which an attempt has been made to determine the actual quantity of water vapor and the true total temperature at the compressor outlet are presented herein. These data are used to compute the compressor work input, as outlined in reference 1; and a correlation with measured shaft input, as found by use of a strain-gage torquemeter, is presented.

APPARATUS AND INSTRUMENTATION

Apparatus

A double-entry turbojet-engine compressor was driven by a 9000-horsepower variable-frequency induction motor through a speed increaser. The inlet air passed through a submerged flat-plate orifice into a depression tank housing the compressor. Water was injected into the inlet air stream approximately 10 inches upstream of the front and rear inducer sections of the impeller. The water-air mixture discharged from the impeller through 14 compressor discharge ducts. These discharge ducts were used to provide space for compressor outlet instrumentation (fig. 1) and are not found in the conventional turbojet-engine assembly.

The inlet ducting, the depression tank, and the 14 discharge ducts were insulated to minimize heat transfer between the working fluid and the room air.

Instrumentation

A high-speed strain-gage torquemeter (reference 2) was used to determine the shaft work input. Four torquemeter strain gages were mounted inside the hollow coupling shaft between the speed increaser and the compressor impeller.

Determination of the work input to the compressor from the enthalpy rise with wet compression required the following instrumentation:

(1) Inlet instrumentation: The air weight flow through the compressor was measured with a submerged flat-plate orifice located in a straight section of the inlet ducting. An electric psychrometer was used to determine the specific humidity of the air. A rotameter was installed to measure the weight flow of the water supplied to the compressor, and a thermocouple was used to obtain the water temperature.

Two thermocouple rakes on opposite sides of the depression tank together with two total-pressure rakes and two static-pressure taps were used to determine the state of the inlet air. The wall static-pressure taps were located in the same plane as the thermocouple and the total-pressure rakes. All inlet instrumentation was installed upstream of the water spray nozzles; therefore, conventional unshielded thermocouples were used.

(2) Outlet instrumentation: Compressor-outlet measurements were taken in the discharge ducts approximately $34\frac{1}{2}$ inches downstream of the diffuser turning vanes. Two wall static-pressure taps were installed on either side of the duct. Two total-pressure probes were installed 90° from the static-pressure taps with the depth of immersion equal to one-third the passage diameter. A schematic diagram of the special outlet instrumentation required for this investigation is shown in figure 2.

Sampling probes (fig. 3(a)) designed and developed at the NACA Lewis laboratory were installed to obtain a vapor-air sample at the compressor outlet. A separate investigation was conducted to obtain samplers that would recover a vapor-air mixture free from water droplets. These sampling probes were located in 7 of the 14 compressor discharge ducts in the same plane as the total-pressure probes and static-pressure taps.

Seven wet- and dry-bulb thermocouples located in chambers (fig. 3(b)) were used in conjunction with the vapor-air sampling probes to determine the vapor-air ratio of the samples. A heat exchanger was used to reduce the temperature of the vapor-air samples below the boiling point of water prior to passing the mixture over the wet- and dry-bulb thermocouples. The reduction in temperature was insufficient to condense the vapor in the sample.

Seven shielded thermocouples (figs. 3(c) and 4) designed and developed at the NACA Lewis laboratory were located in the discharge ducts in the same plane as the other outlet instruments. The shielded thermocouples were of a special design that eliminated the possibility of water droplets making contact with the couple. An individual calibration of each thermocouple was made to insure a true total-temperature indication.

METHODS

Procedure

A double-entry centrifugal compressor was operated at an inlet pressure of 14 inches mercury absolute, ambient inlet-air temperature, varying weight flow, and an equivalent impeller speed of 11,800 rpm. The inlet water-air ratios by weight ranged from 0.02 to 0.05.

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Computations

Work input as obtained with the torquemeter was determined in accordance with reference 2. Independent investigations were made to determine the accuracy of the torquemeter and showed that the total work input as determined by this method was accurate to within ±1 percent.

Determination of work input from the enthalpy rise through the compressor was carried out as follows:

(1) Inlet enthalpy: The inlet enthalpy was determined in accordande with reference 1.

(2) Outlet enthalpy: The vapor-air ratio at the compressor outlet was found by use of the sampling probes and the wet- and dry-bulb thermocouples. From the known inlet specific humidity, quantity of water injected into the compressor, and the vapor-air ratio at the compressor outlet, the actual quantity of water droplets at the outlet was computed. These data with the measured compressor-outlet total temperature and total pressure were used to compute the outlet enthalpy (reference 1).

The work input was determined from the enthalpy rise and the air weight flow through the compressor.

RESULTS AND DISCUSSION

A correlation between the compressor work input as determined from the thermodynamic method of reference 1 and from the shaft input method is presented in figure 5. When the concentration of water droplets at the compressor-outlet measuring station is small, the work input as determined from the enthalpy rise agrees quite well with that obtained by mechanical means. As the concentration of water droplets is increased, a more pronounced scattering of the data results. Variations in the compressor work input include those due to inaccuracies in measurements of compressor air weight flow and compressor torque, which may together have a cumulative error of ±2 percent.

Although theoretically the outlet measurements may be taken at any measuring station after the impeller exit, the scatter of data at high water droplet-air ratios indicates that the outlet instruments should be located as far downstream as possible where maximum evaporation will have taken place.

CONCLUDING REMARKS

2041 From the measured quantity of water vapor and the measured total temperature at the compressor outlet, the work input to a centrifugal compressor operating with water injection has been determined by thermodynamic means. When the concentration of water droplets at the compressor-outlet measuring station is small, the work input as determined from the enthalpy rise agrees quite well with that obtained by mechanical means. As the concentration of water droplets is increased, a more pronounced scattering of the data results.

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REFERENCES

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2. Rebeske, John J., Jr.: Investigation of a NACA High-Speed Strain-Gage Torquemeter. NACA TN 2003, 1950.

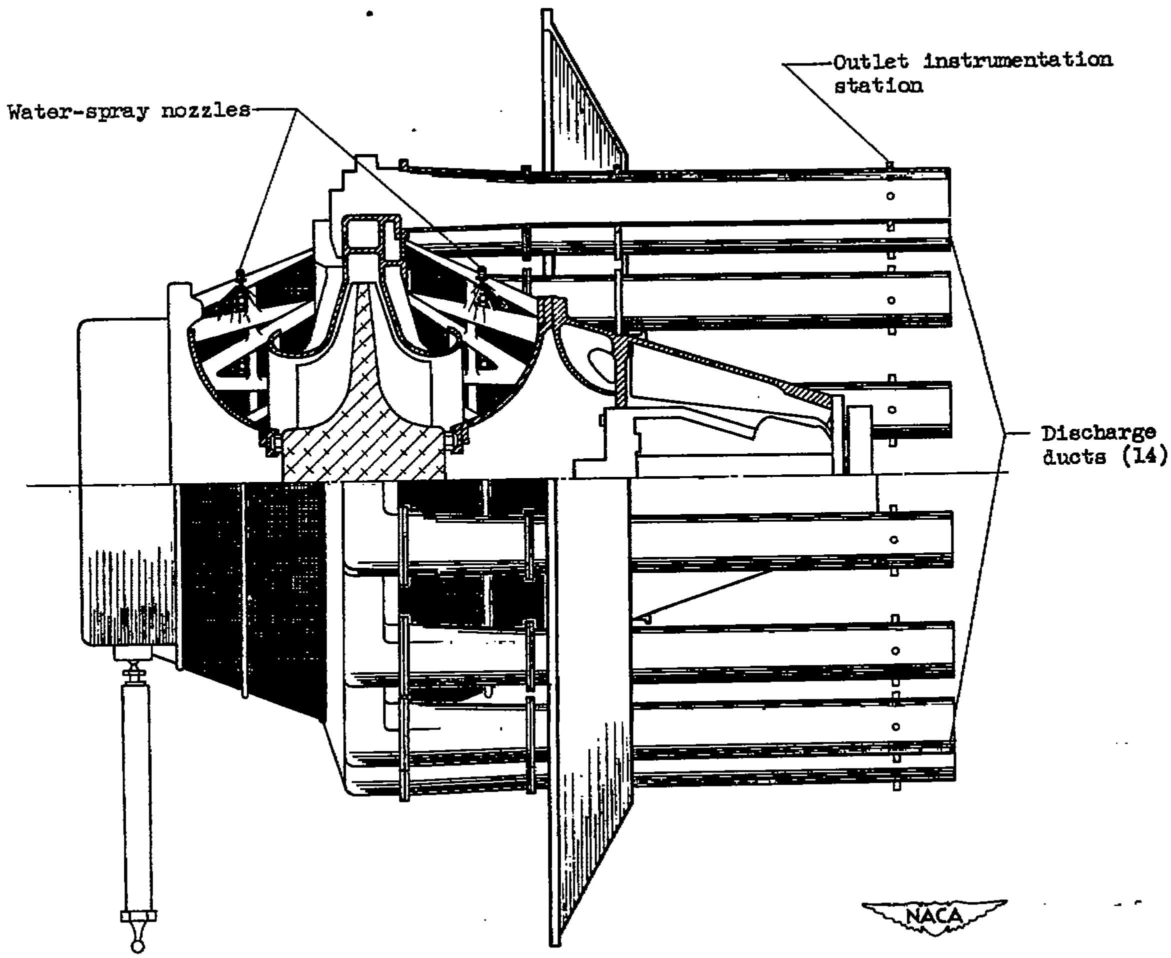

Figure 1. - Schematic section of double-entry centrifugal compressor used in determination of work input when water is injected.

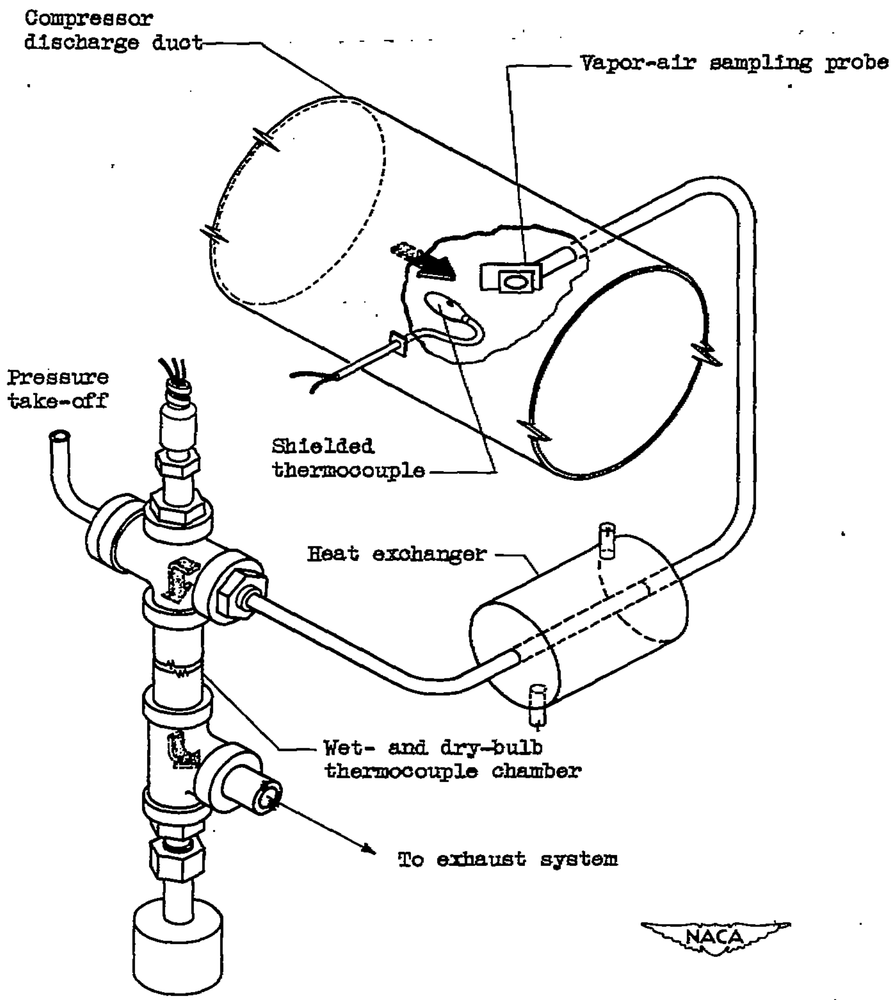

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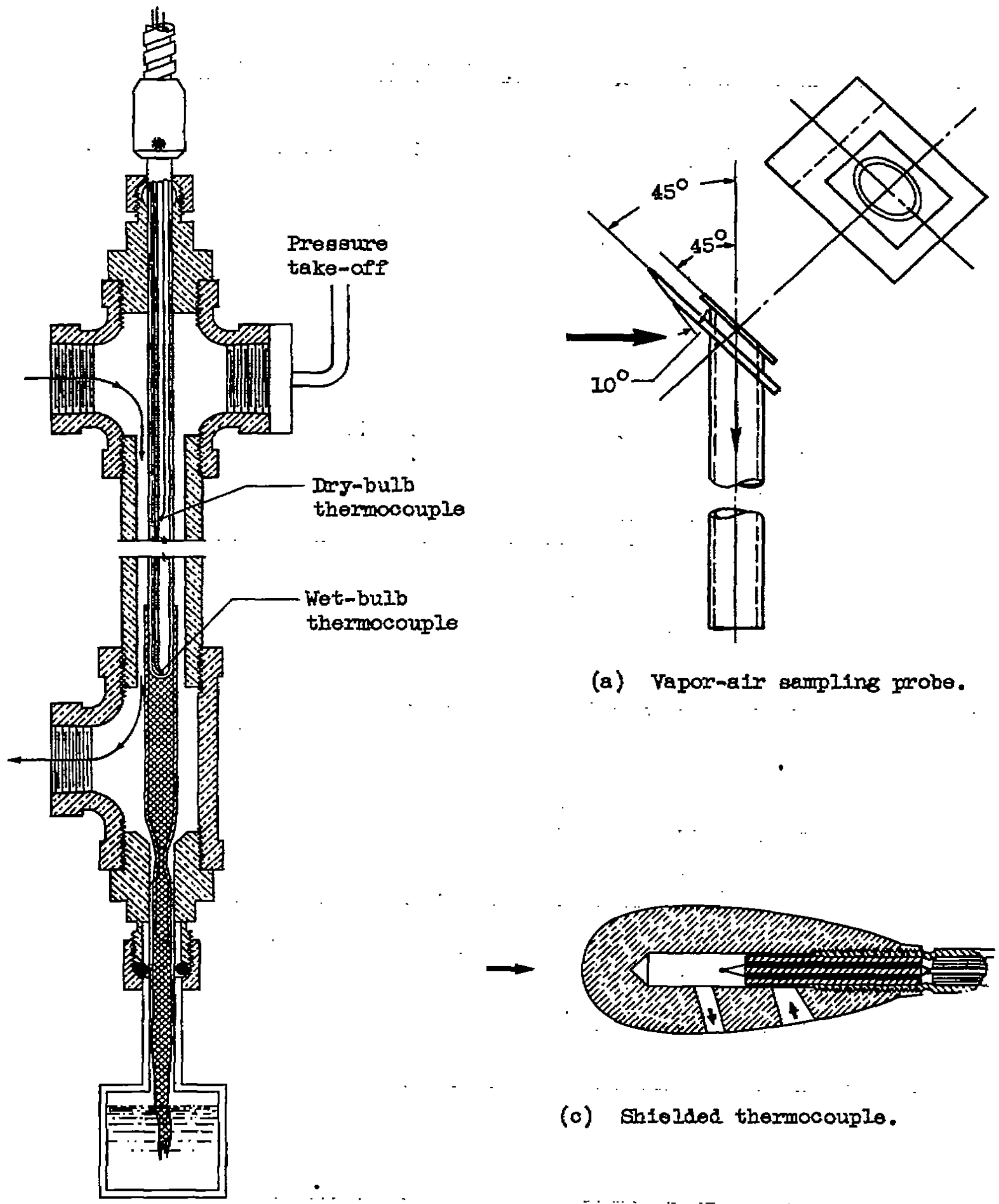
Figure 2. - Special compressor-outlet instrumentation for compressor operating with water injection.



(a) Vapor-air sampling probe.

(c) Shielded thermocouple.

(b) Wet- and dry-bulb thermocouple chamber.

Figure 3. - Outlet instrumentation for centrifugal compressor operating with water injection.

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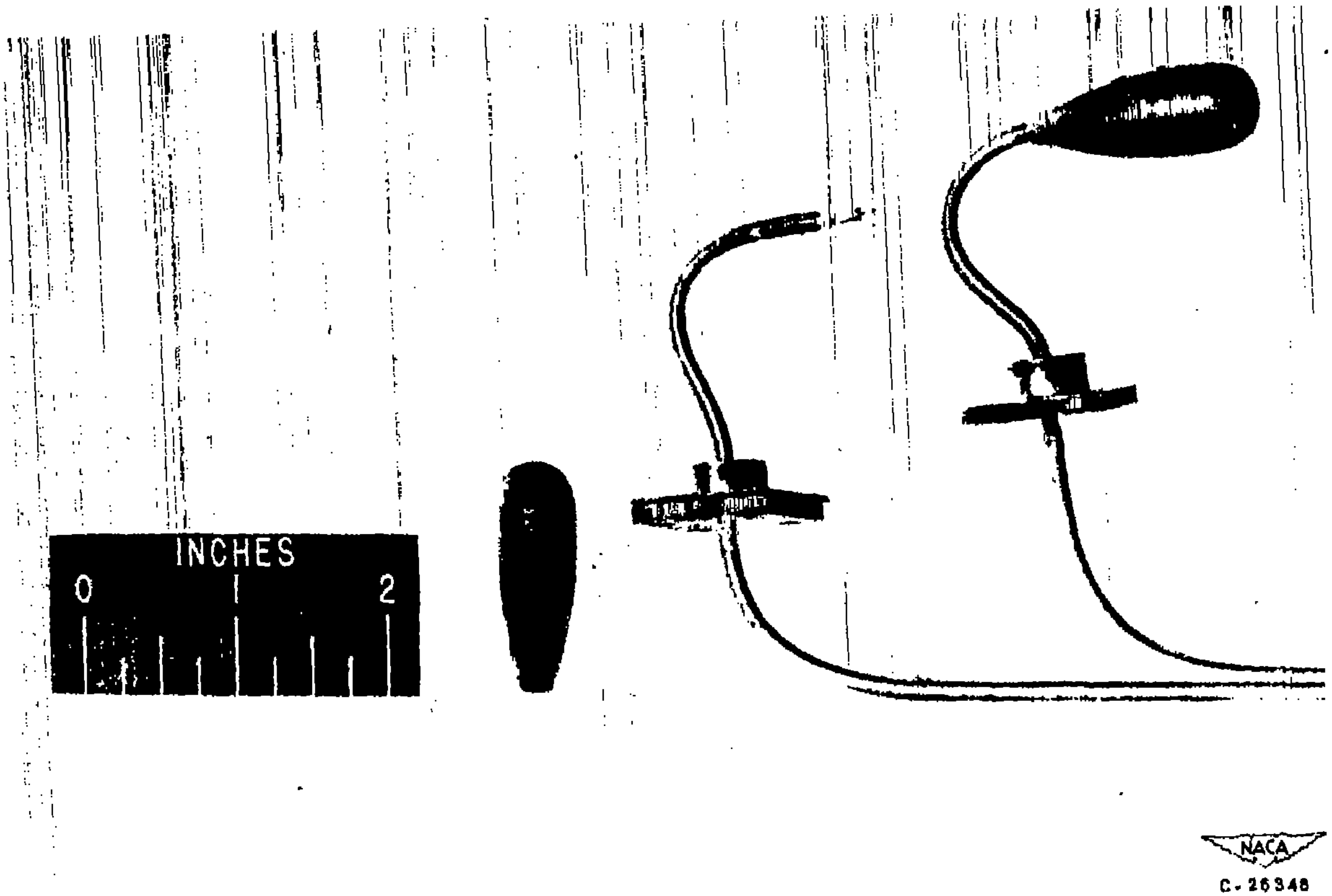

Figure 4. - Shielded thermocouple.

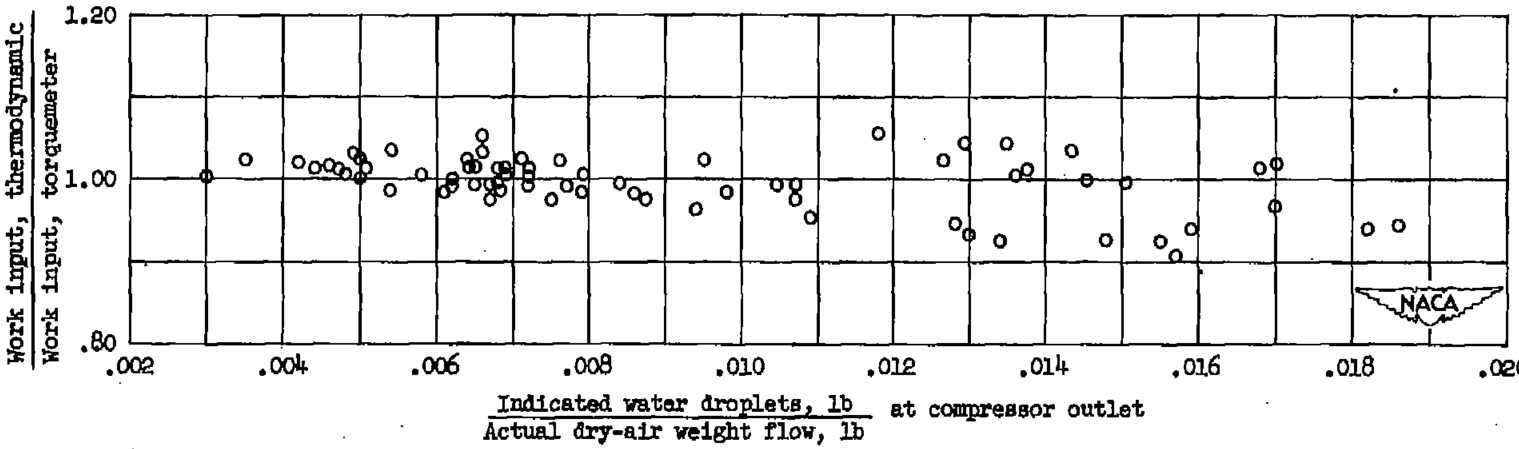

Figure 5. - Correlation between compressor work input as determined from enthalpy rise and from torquemeter measurements.